Year: 2004

The baryonic mass-velocity relation: clues to feedback processes during structure formation and the cosmic baryon inventory

Mayer, Lucio ; Moore, Ben

Abstract: We show that a global relation between baryonic mass and virial velocity can be constructed from the scale of dwarf galaxies up to that of rich galaxy clusters. The slope of this relation is close to that expected if dark matter haloes form in the standard hierarchical cosmogony and capture a universal baryon fraction, once the details of halo structure and the adiabatic contraction of haloes due to cooling gas are taken into account. The scatter and deficiency of baryons within low-mass haloes (Vvir < 50 km s−1) are consistent with the expected suppression of gas accretion by photoevaporation due to the cosmic UV background at high redshift. The data are not consistent with significant gas removal from strong supernovae winds unless the velocities of galaxies measured from their gas kinematics are significantly lower than the true halo velocities for objects with Vvir < 100 km s−1. Thus models such as Λ cold dark matter (ΛCDM) with a steep mass function of haloes may find it difficult to reproduce the baryonic mass-velocity relation presented here whilst at the same time reproducing the flat luminosity/H i function of galaxies. Galaxies hold about 10 per cent of the baryons in the Universe, which is close to the collapsed mass fraction expected within hierarchical models on these scales, suggesting a high efficiency for galaxy formation. Most of the baryons are expected to be evenly distributed between diffuse intergalactic gas in low-density environments and the intragalactic medium within galaxy groups

DOI: https://doi.org/10.1111/j.1365-2966.2004.08203.x

Originally published at:
Mayer, Lucio; Moore, Ben (2004). The baryonic mass-velocity relation: clues to feedback processes during structure formation and the cosmic baryon inventory. Monthly Notices of the Royal Astronomical Society, 354(2):477-484.
DOI: https://doi.org/10.1111/j.1365-2966.2004.08203.x

Mon. Not. R. Astron. Soc. **354,** 477–484 (2004) doi:10.1111/j.1365-2966.2004.08203.x

The baryonic mass–velocity relation: clues to feedback processes during structure formation and the cosmic baryon inventory

Lucio Mayer★ and Ben Moore

Institute of Theoretical Physics, University of Zürich, Winterthurerstrasse 190, 8057 Zurich, Switzerland

Accepted 2004 July 8. Received 2004 July 8; in original form 2003 September 17

ABSTRACT

We show that a global relation between baryonic mass and virial velocity can be constructed from the scale of dwarf galaxies up to that of rich galaxy clusters. The slope of this relation is close to that expected if dark matter haloes form in the standard hierarchical cosmogony and capture a universal baryon fraction, once the details of halo structure and the adiabatic contraction of haloes due to cooling gas are taken into account. The scatter and deficiency of baryons within low-mass haloes ($V_{\rm vir} < 50$ km s^{-1}) are consistent with the expected suppression of gas accretion by photoevaporation due to the cosmic UV background at high redshift. The data are not consistent with significant gas removal from strong supernovae winds unless the velocities of galaxies measured from their gas kinematics are significantly lower than the true halo velocities for objects with $V_{\rm vir} < 100$ km s^{-1}. Thus models such as Λ cold dark matter (ΛCDM) with a steep mass function of haloes may find it difficult to reproduce the baryonic mass–velocity relation presented here whilst at the same time reproducing the flat luminosity/H I function of galaxies. Galaxies hold about 10 per cent of the baryons in the Universe, which is close to the collapsed mass fraction expected within hierarchical models on these scales, suggesting a high efficiency for galaxy formation. Most of the baryons are expected to be evenly distributed between diffuse intergalactic gas in low-density environments and the intragalactic medium within galaxy groups.

Key words: galaxies: haloes – galaxies: kinematics and dynamics – cosmology: theory.

1 INTRODUCTION

Rotational velocities and luminosities of disc galaxies combine to yield the well-known Tully–Fisher relation (Tully & Fisher 1977) across several decades of galaxy masses. The break in the Tully–Fisher relation at velocities lower than $\sim$90 km s^{-1} is removed once total baryonic masses, including gas masses, are used instead of luminosities (McGaugh et al. 2000, hereafter MC00). Many faint disc galaxies are indeed gas-rich, with the neutral hydrogen component often outweighting the stellar mass (Schombert, McGaugh & Eder 2001). The latter 'baryonic' Tully–Fisher relation is well defined down to velocities as low as 50 km s^{-1}, with the small intrinsic scatter possibly due to the spread in stellar mass-to-light ratios resulting from reasonable variations in the star formation histories (Verheijen 1997). The slope of the baryonic Tully–Fisher relation measured by MC00 is close to 4. Because the relation links the amount of baryons within galaxies with their overall potential/total mass (through the rotational velocity), it reflects a tight coupling between dark matter and baryons and hence provides an important test for galaxy formation models. Taken at face value, the observed slope might be too steep compared with the slope of the relation between the virial mass and the peak velocity of haloes expected in a concordance Λ cold dark matter (ΛCDM) model ($\approx$3.5 – see Bullock et al. 2001, hereafter B01). However, the baryons themselves can modify the mass profile as a result of adiabatic contraction (Blumenthal et al. 1986), which raises the peak velocity – an effect that must be taken into account when comparing theory with observations.

The apparent break existing in the Tully–Fisher relation at low velocities has often been interpreted as evidence for a strong effect of supernovae feedback that ejects baryons from galaxies (Dekel & Silk 1986). The absence of a break in the observed baryonic Tully–Fisher relation does not support these feedback models (MC00). However, it is not clear whether this is true for even for fainter, more extreme dwarf galaxies, like those that populate the outer fringes of the Local Group (with measured rotational velocities lower than 50 km s^{-1}; see Mateo 1998). Indeed, although the most sophisticated numerical models of supernovae explosions suggest that even at such low galactic masses only a very small fraction of the total gas mass can be removed by supernovae winds (Mac Low & Ferrara 1999; Mori, Ferrara & Madau 2002), the need to suppress the overcooling in galaxies (White & Frenk 1991) and the failure of cosmological simulations with hydrodynamics to form realistic discs is usually taken as a strong motivation for the need of strong supernovae winds

★E-mail: lucio@physik.unizh.ch

(Navarro & White 1993; Navarro & Steinmetz 2000; Thacker & Couchman 2001; but see Governato et al. 2004). These winds would eject significant amounts of gas in small, early forming objects, quenching galaxy formation at small scales and leaving a larger amount of diffuse, higher angular momentum gas available to form larger galaxies that will be assembled later. A low efficiency of galaxy formation, suggestive of strong feedback mechanisms, is also advocated in the recent estimate of the baryonic mass function of galaxies by Bell et al. (2003), who find that less than 13 per cent of the total number of baryons in the Universe are found in galaxies.

The cosmic UV background at high redshift was strong enough to significantly suppress the collapse of gas in small haloes (Benson et al. 2002a,b, 2003) and might provide a feedback mechanism capable of explaining why the number of luminous galaxy satellites of the Milky Way is much lower than expected from the theory (Kauffmann et al. 1993; Moore et al. 1999; B01). On the larger mass scales of groups and clusters of galaxies, strong pre-heating of gas at high-redshift, by either supernovae or active galactic nuclei (AGNs) (Bower et al. 2001; Borgani et al. 2002), has also been invoked to explain the steepening of the relation between the X-ray luminosity and the X-ray temperature of the hot virialized gas towards decreasing masses (e.g. Borgani et al. 2002). However, there are claims that radiative cooling alone might account for most of this effect (Bryan 2000; Dave et al. 2001).

In this paper, we report on a first attempt to extend the baryonic Tully–Fisher relation both to lower masses, by including the faintest disc galaxies known, and to larger masses, up to rich clusters of galaxies. The implications of our results on the role of feedback mechanisms in structure formation will be discussed. We will then revisit the distribution of baryons in the Universe within the concordance cosmological model.

2 CONSTRUCTION OF THE SAMPLE

We use a variety of data sets to construct the extended baryonic Tully–Fisher relation. (We assume $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ throughout.) The total baryonic masses of systems are inferred directly by observations employing a variety of tracers, from H I and mostly near infrared photometry in galaxies to hot ionized gas measured through its X-ray emission in clusters. For bright galaxies, our analysis is mostly based on the data published by MC00 (these are already a combination of different samples, with photometry in *B*, *H*, *I* and *K* bands) to which we add recent *B*-band photometry and H I kinematics of dwarf galaxies from Stil & Israel (2002a,b) and the data on the outer Local Group dwarf irregular galaxies from Mateo (1998). Note that we do not include the very nearby dwarf spheroidals because the structure of these galaxies may have been substantially reshaped by the tidal interactions with the Milky Way and M31 (Mayer et al. 2001). We also stress that the baryonic mass estimated for galaxies is more precisely the sum of the stars and the cold gas component (the latter is the mass of H I augmented by the mass in helium and metals but with no molecular hydrogen, computed as in MC00). We do not take into account the eventual contribution of a warm/hot ionized medium in their haloes or discs because the quantitative information from observations is still poor; however, we will discuss the impact that this would have on the estimates of the total baryonic content of galaxies in light of recent observations in Section 4.

For clusters, we use two data sets: one from Ettori & Fabian (1999), which contains 36 rich clusters observed with *ROSAT*, and one from Ettori, De Grandi & Molendi (2002) containing 50 clusters with a slightly lower average temperature observed by *BeppoSax*. The same method was used in these two latter papers to derive cluster masses using fits to Navarro–Frenk–White (NFW) profiles (Navarro, Frenk & White 1995). For groups, we use the small sample by Mulchaey et al. (1996), which, to our knowledge, is the only one providing an estimate of both gas masses and total stellar masses which are non-negligible in groups. We assume a fixed stellar mass-to-light ratio (in any given band) to compute the stellar mass from the luminosity of galaxies; we follow MC00 (from which the largest sample is drawn), and therefore $(M/L_{*K}) = 0.8$ and $M/L_{*B} = 1.4$ [these stellar mass-to-light ratios are based on a stellar population synthesis model originally developed by de Jong (1996), assuming a Salpeter stellar initial mass function (IMF); see MC00 for details].

We have to make some assumptions to derive the virial circular velocity, $V_{\rm vir}$, from kinematics of galaxies or from the measured temperature of the intracluster medium. These assumptions are based on the current paradigm of structure formation within a CDM scenario. Hereafter we will assume the standard ΛCDM model ($\Omega_0 = 0.3$, $\Lambda_0 = 0.7$, $\sigma_8 = 0.9$).

We begin by describing the procedure followed to derive $V_{\rm vir}$ for galaxies. Circular velocity profiles of CDM haloes are not flat; they reach a peak value, $V_{\rm peak}$, at some inner radius and then fall out gently to the virial value, $V_{\rm vir}$. The ratio $V_{\rm peak}/V_{\rm vir}$ depends on the concentration, $c = R_{\rm vir}/\,r_{\rm s}$, where $R_{\rm vir}$ is the halo virial radius and $r_{\rm s}$ is the halo scale radius. We have $V_{\rm peak} = [c f(c)]^{1/2} V_{\rm vir}$, with $f(c) = \{4.63[\ln(1 + c) - c/(1 + c)]\}^{-1}$ (B01). Kinematical data are normally limited to the inner regions of the galaxies, hence only $V_{\rm peak}$ is accessible (we discuss later the possibility that even $V_{\rm peak}$ has not really been measured for many dwarf galaxies). For galaxies with resolved rotation curves, $V_{\rm peak}$ is typically identified with the flat portion of the rotation curve, otherwise the half-line width is taken as a reference value (see MC00 and Gonzalez et al. 2000). $V_{\rm vir}$ can be than computed from $V_{\rm peak}$ by means of the function $f(c)$. Cosmological simulations (B01) show that the mean value of $f(c)$ changes by less than 30 per cent between 10^{11} and a few times $10^{12}\,\mathrm{M_\odot}$ due to the mild trend of increasing concentration with decreasing halo virial mass – the mean value of c varies between 10 and 18 in this mass range; galaxies with $V_{\rm peak} > 70\,\mathrm{km\,s^{-1}}$ are expected to have a virial mass larger than $10^{11}\,\mathrm{M_\odot}$ (B01), and hence for them we assume $c = 14$. The rotation curves of many dwarf and low-surface-brightness galaxies often suggest the presence of a constant density core instead of the inner cusp of the NFW profile (de Blok, McGaugh & Rubin 2001a,b; de Blok & Bosma 2002). However, here we are not interested in the mass distribution near the centre of galaxies. Instead, we want to estimate the global parameters of a given system, and in this respect we rely on the fact that reasonable NFW fits to most of the extent of the rotation curve can be obtained provided that one uses concentrations in the range 3–8, significantly lower than expected in ΛCDM models at the scale of dwarf galaxies (Van den Bosch & Swaters 2001; Swaters et al. 2003a; Blais-Ouellette, Amram & Carignan 2001). Therefore, we assume $c = 5$ for all galaxies with $V_{\rm peak} < 70\,\mathrm{km\,s^{-1}}$ (note that typical concentrations for such systems, the virial mass of which is lower than $10^{11}\,\mathrm{M_\odot}$, should be $\geqslant 18$, see B01).

For all galaxies with $V_{\rm peak} > 70\,\mathrm{km\,s^{-1}}$, we also take into account the steepening of the rotation curve owing to the infall of baryons and the resulting adiabatic contraction of the halo during galaxy formation (Blumenthal et al. 1994). For a given halo concentration, this latter correction further lowers the value of $V_{\rm vir}$ calculated from a given value of $V_{\rm peak}$. For these galaxies, the overall mapping between $V_{\rm vir}$ and $V_{\rm peak}$, including the effects of different halo concentration and the response of the halo due to baryonic infall, is calculated using the fitting function by Mo et al. (1998). This latter effect yields $V_{\rm peak}$ as a function of V_{200} (the circular velocity at an overdensity equivalent to 200 times the background density), the halo spin parameter λ, c, the disc mass fraction $f_{\rm d}$ and the ratio between disc and halo specific angular momentum, $j_{\rm d}/j_{\rm h}$. It reads:

$$f_V = V_{\rm peak}/V_{200}$$
$$= \left(\frac{\lambda'}{0.1}\right)^{-2.67 f_{\rm d} - 0.0038/\lambda' + 0.2\lambda'} \left(1 + 4.35 f_{\rm d} - 3.76 f_{\rm d}^2\right)$$
$$\times \frac{1 + 0.057c - 0.00034c^2 - 1.54/c}{[-c/(1+c) + \ln(1+c)]^{1/2}},$$

where $\lambda' \equiv (j_{\rm d}/j_{\rm h})\lambda$. We set $j_{\rm d}/j_{\rm h} = 1$, implicitly assuming that dark matter and baryons start with the same specific angular momentum and that baryons conserve it during collapse (see Mo et al. 1998). We use the formula, assuming that $V_{\rm vir} = V_{200}$; $V_{\rm vir}$ indeed corresponds to an overdensity of $\sim$100 in a ΛCDM model, thus $V_{\rm vir} < V_{200}$, which means we are being conservative in calculating the correction. Assuming the most probable value for the halo spin ($\lambda = 0.035$, see Gardner 2001) and a conservative value for the disc mass fraction $f_{\rm d} = 0.05$ (e.g. Jimenez, Verde & Oh 2003), we obtain $f_V{}^{-1} = 0.53$ for $c = 14$ haloes. This is the correction applied to all galaxies in this mass range.

We do not apply the correction for baryonic infall to galaxies with $V_{\rm peak} < 70$ km s^{-1}; in fact, photoionization at high redshift should have substantially reduced the infall of baryons within small haloes, leaving their dark matter circular velocity profiles nearly unaffected by the baryons (Quinn, Katz & Efstathiou 1996; Gnedin 2000). For these galaxies, we only correct for the effect of halo concentration, $V_{\rm vir}/V_{\rm peak} = 0.93$, as is expected based on the relation of B01 for haloes with $c = 5$.

Finally, when a measure of the gas velocity dispersion exists, and its contribution to the kinematics is non-negligible, it is taken into account by defining $V_{\rm peak} = \sqrt{V_{\rm rot}{}^2 + \beta\sigma^2}$ (σ is the 1D, line-of-sight velocity dispersion and $V_{\rm rot}$ is the rotational velocity), which follows from the virial theorem (Swaters et al. 2003b). We assume isotropic velocity dispersion ($\beta = 3$). Such correction is significant only for the faintest dwarf irregular galaxies ($V_{\rm peak} < 50$ km s^{-1}). At most it accounts for nearly 50 per cent of the total measured velocity of the gas, such as in the faintest objects such as the Local Group dwarfs GR8 and the Sagittarius Dwarf Irregular Galaxy (SagDIG) ($M_B > -13$). Note that including the gas velocity dispersion always raises the computed $V_{\rm peak}$, and therefore $V_{\rm vir}$, and thus its effect goes in the opposite direction of the other two corrections.

For clusters and groups, we use X-ray temperatures of the diffuse hot gaseous medium to infer the 1D velocity dispersion, σ, under the assumption that the system is in virial equilibrium, $T_{\rm vir} \simeq 0.13\,\sigma^2 \mu m_{\rm p}/k_B$ (see Binney & Tremaine 1987), where the molecular weight is $\mu = 0.5989$ (we assume ionized gas with cosmological abundances) and $m_{\rm p}$ is the mass of the proton. The velocity dispersion is then used to determine the circular velocity by simply assuming the asymptotic relation valid for an isothermal potential, $V_{\rm vir} \sim \sqrt{2}\sigma$, which is approximately valid even for an NFW profile (Taffoni et al. 2003). We use the gas masses measured within the outermost radius for all clusters; this radius is between 1 and 1.5 Mpc and we assume that it is a good estimate of the virial radius (if the true virial radius is larger, we should only slightly underestimate the total gas mass given the steep outer slope of the NFW profile).

For some of the groups and clusters, it is possible to compare the masses inferred from using the X-ray data and optical velocity dispersion data. We found that the agreement is very good for all clusters, whereas for some groups, especially those with X-ray emission not centred and not smooth, the resulting dispersions are smaller than those derived from kinematics, which in turn results in smaller virial masses. When the disagreement is strong, we remove the group from the sample as this might indicate an unbound system – or, at least, a non-virialized one. We caution that the properties of galaxy groups are the most uncertain among the different data sets; the extent of the X-ray emission is limited by instrumental sensitivity and probably only a fraction of the virial radius is probed (Mulchaey & Zabludoff 1998). As a consequence, the estimated gas masses for groups are simply lower limits.

3 THE EXTENDED BARYONIC MASS–VELOCITY RELATION

In Fig. 1, we show that a baryonic mass–velocity relation holds across the entire range of scales of virialized objects. The line shown follows the expected mass–velocity relation of dark haloes in a ΛCDM model, where $M_{\rm vir} \sim V_{\rm vir}{}^3$. To derive the latter relation, we calculate the baryonic mass $M_{\rm bar}$ at any given value of the circular velocity $V_{\rm vir}$ as $M_{\rm bar} = f_{\rm b} M_{\rm vir}$, where $f_{\rm b}$ is the universal baryon fraction, with a best estimate of $f_{\rm b} = 0.17$ (Spergel et al. 2003), and $M_{\rm vir}$ is the virial mass at a given $V_{\rm vir}$ expected for virialized haloes in a standard ΛCDM model.

Fig. 1 also shows that the uncorrected data fall typically well below the theoretical prediction, as was argued in the past (MC00). However, data and theory can be brought into a reasonable agreement once the corrections for halo concentration and the effect of baryons described in the previous section are taken into account. We stress that applying the correction for the effect of baryonic infall on the rotation curve is essential to reach consistency with the theoretical curve at galaxy scales. In fact, for galaxies with $c = 14$, the correction for halo concentration alone would yield $V_{\rm vir} = 0.769 V_{\rm peak}$ based on B01, hence accounting for less than half of the shift along the velocity axis for the data points of objects with $V_{\rm peak} > 70$ km s^{-1} (see the bottom plot in Fig. 1). We also note that the halo concentrations depend on the normalization of the power spectrum, and hence on σ_8. In this paper, we assume $\sigma_8 = 0.9$, and that lower/higher values will yield lower-/higher-concentrated haloes and thus a smaller/bigger correction to the observed $V_{\rm peak}$, respectively. Although a mean relation exists, the data deviate from the simplest theoretical prediction at group scales (near $V_{\rm vir} =$ 300 km s^{-1}) and at the scale of the smallest dwarf galaxies, corresponding to $V_{\rm vir} < 50$ km s^{-1}. The best-fitting curve on galactic scales would have a steeper slope of around 3.4.

The deviations from a mean relation can be seen as a deficit of baryons at a given value of the circular velocity. The opposite interpretation, namely an overestimate of the circular velocity, is highly unlikely, at least for galaxies, because the observed velocities have been reduced as much as possible following the assumption that the data yield a value for $V_{\rm peak}$ – if some of the rotation curves are still rising, we would be underestimating $V_{\rm vir}$.

The deviation and increased scatter at dwarf galaxy scales can be easily explained as a result of photoionization by the UV background at high redshift. Semi-analytical models and numerical simulations (Quinn et al. 1996; Thoul & Weinberg 1996; Bullock et al. 2000; Benson et al. 2002a,b) suggest that gas collapse might have been substantially inhibited for objects with $V_{\rm vir} < 50$ km s^{-1} once reionization begins. At even lower circular velocities, evaporation of gas that had already collapsed might also take place (Barkana & Loeb

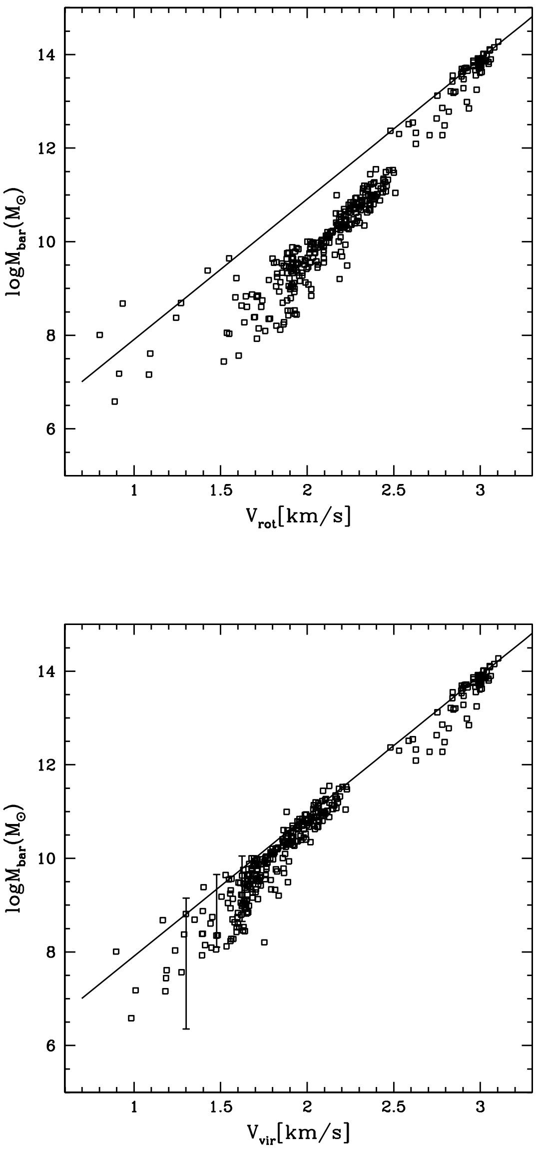

Figure 1. The baryonic mass–velocity relation. The raw data points (squares) are shown in the upper plot and those corrected along the (logarithmic) velocity axis as described in the text are presented in the lower plot. The solid line shows theoretical relation between virial mass and virial velocity predicted by the standard ΛCDM model (a top-hat collapse model has been used). The error bars show the spread of baryonic masses at a given halo circular velocity according to the simulations of Tassis et al. (2003) that include photoionization but no supernovae feedback.

1999; Shaviv & Dekel 2004). These previous results may need some re-interpretation in light of a possible early epoch of reionistation suggested by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) (Spergel et al. 2003)

In Fig. 1, we also compare our results with the predictions from some of the highest resolution simulations of early galaxy formation that include the cosmic UV background (Tassis et al. 2003). We observe a good agreement between the observations and simulations in both the scatter and deficiency of baryons within small galaxies. Simulations from the same authors that also include the effect of thermal and kinetic heating by supernovae find that the minimum baryonic masses would be up to three orders of magnitudes lower than shown in Fig. 1. However, they are similar to the semi-analytic model predictions discussed later.

One could argue that our analysis is missing galaxies with very low baryon fractions simply because they would be too faint to be seen. These objects might be purely gaseous or have very high mass-to-light ratios. A significant population of the gas-rich objects in the local Universe seems to be ruled out by recent wide-field H I surveys (Zwaan et al. 2003), but the second possibility cannot be excluded at the moment.

The simulations of Tassis et al. (2003) that include strong supernovae feedback predict that even fairly bright spiral galaxies, with masses well in excess of 10^{11} $M_{\odot}$, corresponding to $V_{\rm vir} \geqslant 100$ km s^{-1}, would have an average baryon fraction almost an order of magnitude lower than the cosmological value, lying well below the relation reported in Fig. 1. However, we caution that Tassis et al. (2003) stop their simulations at $z = 3$. Present-day bright disc galaxies probably form during a fairly quiescent phase of smooth gas accretion at lower redshift, once the merger rate has dropped significantly (Thacker & Couchman 2001; Governato et al. 2004). As their potential well grows and the star formation rate – and thus the rate of supernovae explosions – drops, they should retain an increasing fraction of the newly accreted baryons, eventually moving upwards along the baryonic mass axis of Fig. 1.

Our results suggest that supernovae winds do not eject significant baryonic mass from galaxies. This, however, does not mean that feedback is not important as a regulating mechanism for the ambient gas temperature and density, and thus for star formation in galaxies both small and large.

It is notable that the baryonic Tully–Fisher relation has such a small scatter across most of the galaxy population. As already pointed out by MC00, variations of the stellar mass-to-light ratio due to different star formation histories would already account for most of the scatter along the vertical axis, leaving little room for variation in the IMF of stars. Along the horizontal axis, a scatter of 0.4 in $\log(V_{\rm vir})$ would be expected if, at a fixed value of the concentration, we vary λ in the range $0.01 - 0.1$ and $f_{\rm d}$ in the range 0.01–0.15. These variations in the main parameters controlling disc formation inside dark haloes already account for the entire scatter in the plot at $V_{\rm vir} \sim 100$ km s^{-1}. Cosmic scatter in the structure of dark haloes alone, which translates into a possible range for the concentration of haloes at a given mass, is expected to produce an additional scatter of roughly 0.2–0.3 in $\log(V_{\rm vir})$ (B01).

Therefore, if we simply sum the effect of the different sources of scatter (which would imply that they are totally independent from each other) we would expect data points to be more scattered than they actually are. A similar problem was already argued by B01 for the Tully–Fisher relation. However, at least in our data sets, the galaxies considered are only late-type objects. Spheroidal components are never dominant and this eliminates a large portion of the available parameter space, and thus of the scatter. In particular, both low-spin objects ($\lambda < 0.03$) and systems with very high disc mass fractions ($f_{\rm d} \geqslant 0.1$) may transform into early-type spirals or S0 galaxies as a substantial fraction of their disc mass transforms into a bulge because of bar formation and secular bar evolution (Combes et al. 1990; Mo et al. 1998). Considering the restricted parameter space ($0.03 < \lambda < 0.1$, $0.01 < f_{\rm d} < 0.1$), the scatter along the horizontal axis due to variations in the conditions of disc formation reduces to less than 0.2 in $\log(V_{\rm vir})$, leaving room for the other possible sources of scatter.

The deviation at group scales is also interesting, although the interpretation is hindered by the small size of the sample considered here. One possibility is that groups contain a substantial mass of gas at temperatures 10^6–10^7 K that has not been observed because it falls below the detection limits of current instruments (Mulchaey & Zabludoff 1998; Burstein & Blumenthal 2002). Alternatively, one may invoke pre-heating and evaporation of gas induced by winds from AGNs, with an effective reduction of the gas masses bound to the groups (Silk & Rees 1998; Bower et al. 2001). Indeed, in a scenario where there is a strong link between the formation of spheroids and supermassive black holes (Ferrarese & Merritt 2000), we can imagine that X-ray-bright groups like those considered here would be affected most. We also note that even at cluster scales several points lie slightly below the theoretical curve. This might indicate that some fraction of the baryonic matter is in a warm undetected phase even at these scales, as recently argued by Ettori (2003).

4 THE BARYON PIE

If galaxies have most of their baryons locked in their discs, it might seem odd that observational measurements of the baryonic mass function of galaxies indicate that these discs contribute only a tenth of the total amount of baryons expected in the Universe (e.g. Bell et al. 2003). However, the question here is how large a contribution do galaxies make to the total (dark + baryonic) mass of the Universe in the first place?

We use a large high-resolution N-body simulation to estimate the contribution of different mass scales to the total mass in a representative volume of the Universe. The ΛCDM simulation (Reed et al. 2003) has a box of size $50\,h^{-1}$ Mpc^{-1} and the particle mass is $1.3 \times 10^8\,h^{-1}\,\mathrm{M}_\odot$, such that it has enough resolution to probe objects as small as the most massive dwarf galaxies in the Local Group (a few times $10^9\,\mathrm{M}_\odot$).

At $z = 0$, we integrate the mass function in different mass bins (Fig. 2) and find for the following broad mass scales:

(i) galaxies: $10^{10}\,\mathrm{M}_\odot < M_{\mathrm{vir}} < 10^{12}\,\mathrm{M}_\odot$ 13 per cent;
(ii) groups: $10^{12}\,\mathrm{M}_\odot < M_{\mathrm{vir}} < 10^{14}\,\mathrm{M}_\odot$ 30 per cent;and
(iii) clusters: $M_{\mathrm{vir}} > 10^{14}\,\mathrm{M}_\odot$ 10 per cent.

Note that among the galaxies we have not included bound systems with masses $10^9\,\mathrm{M}_\odot < M_{\mathrm{vir}} < 10^{10}\,\mathrm{M}_\odot$. These are found in the simulation and contribute another ∼5 per cent to the total mass.

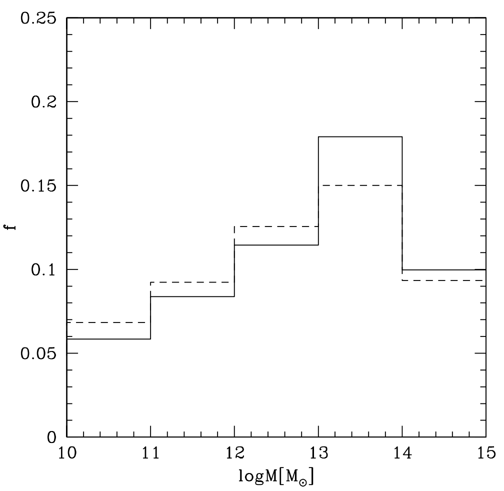

Figure 2. Histogram of the mass fraction in objects of different mass scales in the high-resolution ΛCDM simulation of Reed et al. (2003) (solid line) and for the Sheth & Tormen (1999) mass function model (dashed line). See text for details.

However, even assuming that they have a cosmological baryon fraction, they would have baryonic masses lower than the lower limit in the analysis of Bell et al. (2003). In addition, as we explained above, at these mass scales ($V_{\mathrm{c}} < 40$ km s^{-1}) the effect of photoionization is important – gas that might have collapsed at these scales will more likely end up contributing to a diffuse intergalactic medium (IGM) component (see below). The remaining 42 per cent of the mass is found in the form of a diffuse dark matter component that would be resolved in smaller haloes at higher resolution. Bell et al. (2003), by measuring the mass in stars and cold gas within galaxies (hence at the baryonic mass in their discs), find that the contribution of galaxies to the baryon budget is around 8 ± 5 per cent and interpret this as a low efficiency for galaxy formation. However, this number is quite close to the 13 per cent that we would estimate here for the expected contribution of galaxies to the baryonic pie under the assumption that they captured the cosmological baryon fraction. In fact, galaxies will contribute a fraction $f_{\mathrm{b,gal}} = f_x M_{\mathrm{gal}}/f_{\mathrm{b}} M_{\mathrm{tot}} = (f_x/f_{\mathrm{b}}) f_{M,\mathrm{gal}}$ to the total baryonic content of the Universe, where f_x is the baryonic fraction in galaxies and $f_{M,\mathrm{gal}} = M_{\mathrm{gal}}/M_{\mathrm{tot}}$ is the fractional mass contribution of galaxy-scale objects to the total. If we assume $f_x = f_{\mathrm{b}}$, using the above estimate for $f_{M,\mathrm{gal}}$, namely 13 per cent, it also follows that $f_{\mathrm{b,gal}} = 13$ per cent. This would actually indicate a high efficiency for galaxy formation. The actual fractional contribution of galaxies will be somewhat higher than that because so far we have not counted galaxies that are in groups or clusters and whose mass has been included in the mass bins of clusters and groups. Although the sample of Bell et al. (2003) is based on field galaxies, contamination by galaxies in groups cannot be excluded due to the difficulties in identifying groups observationally. Estimates of the mass fraction in subhaloes in any given host halo range between 10 per cent (e.g. Ghigna et al. 1998; De Lucia et al. 2004) and 18 per cent (Kravtsov et al. 2004; Vale & Ostriker 2004). Substructure in groups having a mass corresponding to what we have identified as galaxies (between 1/10 and 1/1000 of the mass of a group halo) contribute about 10 per cent to the total mass of such group scale objects (quoting the highest values, i.e. those given in Vale & Ostriker 2004). Because groups contribute about 30 per cent to the total mass budget, galaxies in them would contribute 0.1×30 per cent = 3 per cent, which would bring the total contribution of galaxy-scale objects to the baryon budget up to 16 per cent, now somewhat higher than the upper limit quoted by Bell et al. (2003).

However, this mild discrepancy can easily be accommodated if we take into account that not all the baryons in a galaxy need to be in the form of cold gas or stars in the disc as assumed in Bell et al. (2003). Indeed, it is likely that galaxies have a substantial component of hot gas in an extended halo, material that is still cooling inwards onto the disc. Evidence for the existence of this component is gradually accumulating, at least for the Milky Way, thanks to new observations of O VI and X-ray absorption (Kalberla & Kerp 1999; Nicastro et al. 2003; Sembach et al. 2003). These observations suggest that the hot gas could have a density of up to 10^{-4} atom cm^{-3} between 50 and 100 kpc and that its temperature at these distances is less than 2×10^6 K. Further evidence for a hot halo with this density comes from the hydrodynamical model for the Large Magellanic Cloud (LMC)–halo interaction and the Magellanic Stream (Mastropietro et al. 2003). Assuming that the hot gas profile follows the dark matter (NFW) profile, its total mass would be as much as 30 per cent of the Milky Way disc mass.

Groups of galaxies potentially hold the largest fraction of baryons in virialized structures, whilst clusters of galaxies (defined by mass above) would contribute only about 10 per cent. We caution that, due to the modest box size, statistical 1σ Poisson fluctuations in the mass function of objects are between 30 per cent and ~80 per cent at the scale of groups and clusters (see Reed et al. 2003). We checked that the relative contributions of the different components are reliable by comparing with the Sheth & Tormen (1999) mass function (Fig. 2). The comparison confirms that groups are the most important contributors to the baryon budget and that the efficiency of galaxy formation is quite high. The importance of groups for the baryon budget has been noted by many authors in the past, among them Fukugita, Hogan & Peebles (1998).

It is now apparent why clusters and groups contain more baryons in gas than the sum of the galaxies that formed these systems. The volume from which clusters collapse is large enough to capture a large fraction of the low-density IGM, thus giving a final high fraction of diffuse gas.

As we mentioned above, in the ΛCDM simulation about 42 per cent of the mass is diffuse, which is outside (resolved) virialized structures. While this diffuse dark matter component would certainly collapse in smaller structures at even higher resolutions (Moore et al. 1999), most of these small haloes are expected to be dark, thereby not contributing to the baryon budget. Indeed, within haloes of masses $10^3\,M_\odot < M_{\rm vir} < 10^6\,M_\odot$ (the lower limit is given by the cosmological Jeans mass), baryons can cool via molecular hydrogen at very high redshift ($z \geqslant 25$) but would immediately photodissociate H_2, halting baryonic collapse until they achieve masses in the range $M_{\rm vir} > 10^6\,M_\odot$ (corresponding to a virial temperature $T_{\rm vir} > 10^4$ K) and can cool via atomic hydrogen (Haiman, Thoul & Loeb 1996; Haiman, Abel & Rees 2000; Haiman 2003).

At later times, low-mass haloes may reionize the intergalactic medium, suppressing the collapse of baryons at scales up to $M_{\rm vir} \sim 10^9\,M_\odot$. Therefore the diffuse mass in our simulations should mostly trace a truly diffuse IGM baryonic component. This component, together with gas within groups, makes up the dominant contribution to the baryon budget, ≈75 per cent. A substantial amount of 'warm' gas (10^5 K $< T <$ 10^6 K) outside virialized structures would indeed explain the soft X-ray background (Cen & Ostriker 1999; Dave et al. 2001). The same reasoning and the baryon fractions in the different components would also apply to warm dark matter, or other models that have reduced power on small scales (below $10^{10}\,M_\odot$).

5 DISCUSSION

We have shown that a relation between the mass of baryons and the depth of the potential well holds across a wide range of scales, from the smallest dwarf galaxies to galaxy clusters. The mean relation is consistent with the mass–velocity relation expected for most cosmological models in which dark matter haloes grow and collapse through gravitational instability. Deviations from the mean relation at the scale of dwarf galaxies are explained as a result of heating/evaporation from the UV background at high redshift, whereas at group scales we cannot exclude a role of feedback from AGNs (Silk & Rees 1998; Kaiser & Binney 2003). Our results argue against the existence of the 'strong form' of supernovae feedback, namely that capable of substantial removal of baryons in dwarfs (Dekel & Silk 1986; Dekel & Woo 2003).

We believe that it will be an interesting challenge for the standard concordance ΛCDM model to reproduce both the baryonic mass function presented here whilst also producing a luminosity (and H I) function of galaxies with a reasonably flat faint-end slope. Most models in which the dark matter is a collisionless component predict a mass function of dark matter haloes which is much steeper than

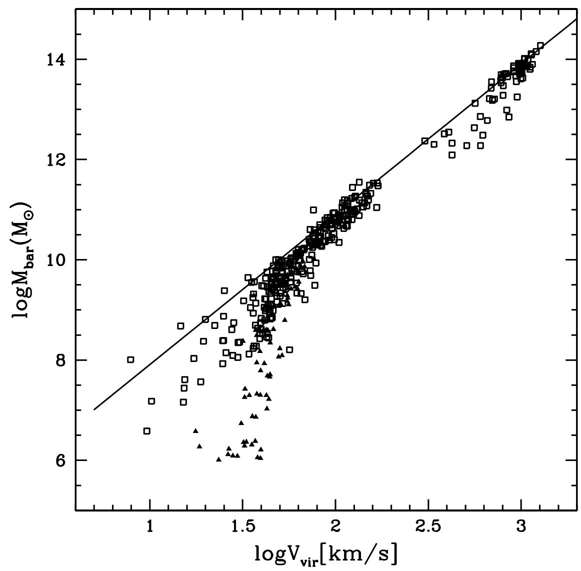

Figure 3. Data points (squares) and theoretical relation (solid line) compared with the results of the Benson et al. (2002a,b) semi-analytical model of galaxy formation (triangles). The semi-analytical model (see Discussion) includes photoionization plus a strong kinetic feedback for small haloes.

the luminosity function of galaxies. These models rely on strong feedback to give rise to a mass dependent mass-to-light ratio to flatten the observed luminosity function of haloes – photoionization alone is not enough (see Benson et al. 2003).

In Fig. 3, we compare our results with the predictions of the Durham semi-analytic galaxy formation models which include both photoionization and supernovae winds (Cole et al. 2000; Benson et al. 2002a,b). In such a model, a large fraction of the energy of supernovae explosions is converted into kinetic energy, suppressing gas cooling and star formation in haloes with low values of $V_{\rm peak}$, as in the numerical simulations of galaxy formation by Navarro & White (1993). This has the expected result of reproducing reasonably well the faint end of the galaxy luminosity function. This form of feedback is not as strong as the superwinds in Benson et al. (2003), which can remove gas even in bright (L_*) galaxies, but still produces objects whose baryonic content falls short of that predicted by the baryonic mass–velocity relation (see Fig. 3). The same models do indeed provide a better fit (within a factor of 2) to the *I*-band Tully–Fisher relation, which of course uses only the luminosities of galaxies (see fig. 7 in Cole et al. 2000); indeed, strong feedback will remove most of the gas in dwarf galaxies – a larger discrepancy shows up in the baryonic Tully–Fisher relation simply because gas accounts for most of the baryons in observed dwarfs (MC00). We note that models with a truncated power spectrum at small mass scales such as would be produced by free streaming of a 1-KeV particle or through an interaction between the dark matter and photons (Boehm et al. 2002) might be able to reproduce these observed correlations. These models should preserve the same scaling properties that allowed us to fit the baryonic mass–velocity relation down to galaxy scales, but would naturally lower the number of low-mass haloes such that the mass function has a linear relation to the luminosity function.

A caveat in the results presented here is that measurements of both the peak velocity and the baryonic masses of galaxies are subject to several uncertainties, especially in the case of dwarf galaxies. A factor of two variation in the stellar masses of galaxies is indeed

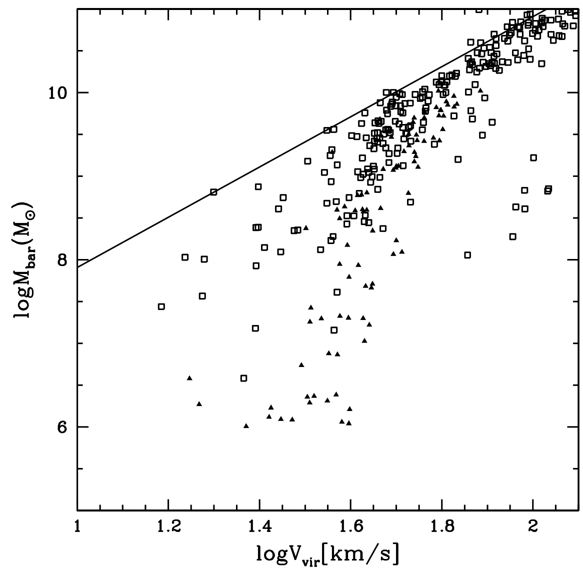

Figure 4. As Fig. 3, but only showing the comparison for the lower-mass systems and for virial velocities set equal to twice the measured maximum velocity (see Section 4 for discussion on this correction) in the case of galaxies with $V_{\rm rot} < 50$ km s^{-1}. Stellar masses are also reduced by a factor of 2 to account for possible uncertainties in the IMF.

easily achieved by changing the IMF of stars (Cole et al. 2001). In addition, the data for the faintest galaxies included in our sample (Stil & Israel 2002a,b; Mateo 1998) do not extend far from the centre such that some have rotation curves which are not clearly flat at the last measured point. In the smallest galaxies, the velocity field of the gas is quite chaotic and is dominated by random motions in the outer part (for example, GR8; see Carignan et al.1990) such that the association of the measured velocity with $V_{\rm peak}$ is uncertain. In these cases, we cannot exclude the fact that we are only probing the inner part of a much bigger system with much higher velocity, which would move the data points to the right in Fig. 3, towards the predictions of the semi-analytical models. A similar argument has been made by Stoehr et al. (2002) to fix the comparison between the observed number of galactic satellites and that predicted in the ΛCDM model. As a simple exploration of where the data points would lie if we push the systematic effects in favour of CDM models, in Fig. 4 we show the data points after allowing both a factor of 2 increase in the true halo virial velocity (this being quantitatively consistent with the predictions of Stoher et al.) and a factor of 2 decrease in the stellar mass of galaxies due to a different IMF – the correction to the velocity is applied only to galaxies with measured velocities <50 km s^{-1} because these have the more poorly determined rotation curves. In this case, there is a better agreement with the predictions of semi-anaytical models, but they still do not overlap.

How does our Galaxy fit in the picture presented so far? According to the results of Fig. 1, the Milky Way, in order to be 'typical' for a baryonic mass $\lesssim 10^{11}$ M$_\odot$, as suggested by its K-band luminosity (Kochanek et al. 2001), must have $V_{\rm vir} \lesssim 130$ km s^{-1} and a total virial mass $\sim 10^{12}$ M$_\odot$. Such a model for the Milky Way is plausible based on its rotation curve and on the other observational constraints available and, in particular, is in agreement with the most baryonic-dominated, maximum-disc models (Klypin, Zhao & Somerville 2002; Wilkinson & Evans 1999). The additional 3×10^{10} M$_\odot$ of hot gas in the halo suggested by the LMC kinematics, *FUSE* and *ROSAT* data would imply that we have accounted for all the expected baryons in the Galaxy.

Our analysis does not include individual elliptical galaxies (these of course enter in the global estimates of baryonic masses in groups and clusters). Interestingly, a recent paper by Padmanabhan et al. (2004), which uses photometry and kinematics of almost 30 000 elliptical galaxies with velocity dispersions larger than 70 km s^{-1} taken from the Sloan Digital Sky Survey, finds that the dynamical to stellar masses are between 7 and 30. Taking into account that a typical elliptical galaxy also has a significant hot gaseous X-ray halo, they conclude that these galaxies appear to have captured close to the cosmological baryon fraction, in agreement to what we find here for other types of galaxies.

An additional piece of this complex puzzle is the relationship with the dynamical mass estimates of field galaxies from weak lensing (McKay et al. 2001; Guzik & Seljak 2002). Weak lensing should provide the strongest constraints on the total mass-to-light ratios of galaxies. McKay et al. (2001) obtained very high average mass-to-light ratios, roughly around 100. Such high mass-to-light ratios have been substantially confirmed by independent measurements based on the motion of the satellites in the same galaxies (McKay et al. 2002). These measurements are taken at a fixed projected radius of 260 h^{-1} kpc. Therefore one has no information on the virial radius of individual galaxies, and hence any definition of a virial velocity would be arbitrary. None the less, if we assume that the projected radius is comparable to the virial radius of the galaxies, we obtain virial velocities in the range 131–322 km s^{-1} [from $V_{\rm vir} = \sqrt{(GM_{(R<260h^{-1}{\rm kpc})}/260\,h^{-1}\,{\rm kpc})}$] for baryonic masses in the range 1–8 × 10^{10} L$_\odot$ [this follows from taking the z-band luminosity range probed by McKay et al. (2002) and assuming a stellar mass-to-light ratio $M/L_* = 1$ in this band], whereas our data points would imply virial velocities in the range 60–160 km s^{-1} for the same range of baryonic masses. However, more recently Guzik & Seljak (2002) reanalysed the same Sloan Digital Sky Survey (SDSS) data set, taking into account the effects of clustering and cosmologically motivated models for the halo density profiles. At L_*, they find a virialized dark matter halo to baryon mass ratio of 10. They also comment that this implies a high efficiency in the conversion of baryons to stars. In other words, based on the their analysis the weak lensing data also appear to be consistent with the idea that galaxies have captured the expected baryon fraction and that supernovae feedback has been inefficient at preventing star formation and has not ejected a large fraction (>30 per cent) of baryons into the IGM.

ACKNOWLEDGMENTS

We thank Darren Reed, Fabio Governato and Tom Quinn for allowing us to use their ΛCDM simulation, Andrew Benson, Carlos Frenk and the other members of the Durham theory group for providing us with the results of the Durham semi-analytical models and for stimulating discussions. We also thank Frank Van den Bosch and Andi Burkert for helpful comments on an earlier version of the paper and George Lake for numerous discussions on feedback. We are thankful to the anonymous referee for his remarks and stimulatng comments that considerably improved the paper.

REFERENCES

Barkana R., Loeb A., 1999, ApJ, 523, 54
Bell E. F., McIntosh D. H., Katz N., Weinberg M. D., 2003, ApJ, 585, L117

Benson A. J., Lacey C. G., Baugh C. M., Cole S., Frenk C. S., 2002a, MNRAS, 333, 156
Benson A. J., Frenk C. S., Lacey C. G., Baugh C. M., Cole S., 2002b, MNRAS, 333, 177
Benson A. J., Bower R. G., Frenk C. S., Lacey C. G., Baugh C. M., Cole S., 2003, ApJ, 599, 38
Binney J., Tremaine S., 1987, Galactic Dynamics, Princeton Univ. Press, Princeton, NJ
Blais-Ouellette S., Amram P., Carignan C., 2001, AJ, 121, 1952
Blumenthal G. R., Faber S. M., Flores R., Primack J. R., 1986, ApJ, 301, 27
Boehm C., Riazuelo A., Hansen S. H., Schaeffer R., 2002, Phys. Rev. D., 66, 083505
Borgani S., Governato F., Wadsley J., Menci N., Tozzi P., Quinn T., Stadel J., Lake G., 2002, MNRAS, 336, 409
Bower R. G., Benson A. J., Lacey C. G., Baugh C. M., Cole S., Frenk C. S., 2001, MNRAS, 325, 497
Bryan G. L., 2000, ApJ, 544, L1
Bullock J. S., Kravtsov A. V., Weinberg D. H., 2000, ApJ, 539, 517
Bullock J. S., Kolatt T. S., Sigad Y., Somerville R. S., Kravtsov A. V., Klypin A. A., Primack J. R., Dekel A., 2001, MNRAS, 321, 559 (B01)
Burstein D., Blumenthal G., 2002, ApJ, 574, L17
Carignan C., Beaulieu S., Freeman K. C., 1990, AJ, 99, 178
Cen R., Ostriker J. P., 1999, ApJ, 514, 1
Cole S., Lacey C. G., Baugh C. M., Frenk C. S., 2000, MNRAS, 319, 168
Cole S. et al., 2001, MNRAS, 326, 255
Combes F., Debbasch F., Friedli D., Pfenniger D., 1990, A&A, 233, 82
Dave R. et al., 2001, ApJ, 552, 473
de Blok W. J. G., Bosma A., 2002, A&A, 385, 816
de Blok W. J. G., McGaugh S. S., Rubin V. C., 2001a, A&A, 122, 2381
de Blok W. J. G., McGaugh S. S., Rubin V. C., 2001b, A&A, 122, 2396
de Jong R. S., 1996, A&A, 313, 377
Dekel A., Silk J., 1986, ApJ, 303
Dekel A., Woo J., 2003, MNRAS, 344, 1131
De Lucia G., Kauffmann G., Springel V., White S. D. M., Lanzoni B., Stoehr F., Tormen G., Yoshida N., 2004, MNRAS, 348, 333
Ettori S., 2003, MNRAS, 344, L13
Ettori S., Fabian A., 1999, MNRAS, 305, 834
Ettori S., De Grandi S., Molendi S., 2002, A&A, 391, 841
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Fukugita M., Hogan C. J., Peebles P. J. E., 1998, ApJ, 503, 518
Gardner J. P., 2001, ApJ, 557, 616
Ghigna S., Moore B., Governato F., Lake G., Quinn T., Stadel J., 1998, MNRAS, 300, 146
Gnedin N. Y., 2000, ApJ, 535, 530
Gonzalez A. H., Williams K. A., Bullock J. S., Kolatt T. S., Primack J. R., 2000, ApJ, 528, 145
Governato F. et al., 2004, ApJ, 607, 688
Guzik J., Seljak U., 2002, MNRAS, 335, 311
Haiman Z., 2003, in Bender R., Renzini A., eds, Proc. ESO Workshop, The Mass of Galaxies at Low and High Redshift. Springer, Berlin, p. 316
Haiman Z., Thoul A., Loeb A., 1996, ApJ, 464, 523
Haiman Z., Abel T., Rees M. J., 2000, ApJ, 534, 11
Jimenez R., Verde L., Oh S. Peng, 2003, MNRAS, 339, 243
Kaiser C. R., Binney J., 2003, MNRAS, 338, 837
Kalberla P. M. W., Kerp J., 1999, in Gibson B. K., Putman M. E., eds, ASP Conf. Ser. Vol. 166, Stromlo Workshop on High-Velocity Clouds.Astron. Soc. Pac., San Francisco, p. 170
Kauffmann G., White S. D. M., Guiderdoni B., 1993, MNRAS, 264, 201
Klypin A., Zhao H., Somerville R. S., 2002, ApJ, 573, 597
Kochanek C. S. et al., 2001, ApJ, 560, 566
Kravtsov A. V., Berlind A., Wechsler R. H., Klypin A. A., Gottloeber S., Allgood B., Primack J., 2004, ApJ, 609, 35
McGaugh S. S., Schombert J. M., Bothun G. D., de Blok W. J. G., 2000, ApJ, 533, L99 (MC00)
McKay T. A. et al., 2001, ApJ, submitted (astro-ph/0108013)
McKay T. A. et al., 2002, ApJ, 571, L85
Mac Low M., Ferrara A., 1999, ApJ, 513, 142
Mastropietro C., Moore B., Mayer L., Stadel J., Wadsley J., 2003, in Prada F., Martínez-Delgado D., Mahoney T., eds, ASP Conf. Ser., Satellites and Tidal Streams. Astron. Soc. Pac., San Francisco, in press
Mateo M., 1998, ARA&A, 36, 435
Mayer L., Governato F., Colpi M., Moore B., Quinn T., Wadsley J., Stadel J., Lake G., 2001, 559, 754
Mo H. J., Mao S., White S. D. M., 1998, MNRAS, 96, 847
Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999, ApJ, 524, L19
Mori M., Ferrara A., Madau P., 2002, ApJ, 571, 40
Mulchaey J. S., Davis D. S., Mushotzky R. F., Burstein D., 1996, ApJ, 456, 80
Mulchaey J. S., Zabludoff A. I., 1998, ApJ, 496, 73
Navarro J., Steinmetz M., 2000, ApJ, 538, 477
Navarro J., White S. D. M., 1993, ApJ, 265, 271
Navarro J. F., Frenk C. S., White S. D. M., 1995, MNRAS, 275, 56
Nicastro F. et al., 2003, Nat, 421, 719
Padmanabhan N. et al., 2004, New Astron., 9, 329
Reed D., Gardner J., Quinn T., Stadel J., Fardal M., Lake G., Governato F., 2003, MNRAS, 346, 565
Quinn T., Katz N., Efstathiou G., 1996, MNRAS, 278, L49
Sembach K. R. et al., 2003, ApJS, 146, 165
Schombert J. M., McGaugh S. S., Eder J. A., 2001, AJ, 121, 1420
Shaviv N. J., Dekel A., 2004, MNRAS, submitted (astro-ph/0305527)
Sheth R. K., Tormen G., 1999, MNRAS, 308, 119
Silk J., Rees M. J., 1998, A&A, 331, L1
Spergel D. N. et al., 2003, ApJS, 148, 175
Stil J. M., Israel F. P., 2002a, A&A, 389, 29
Stil J. M., Israel F. P., 2002b, A&A, 389, 42
Stoehr F., White S. D. M., Tormen G., Springel V., 2002, MNRAS, 335, L84
Swaters R. A., Madore B. F., van den Bosch F. C., Balcells M., 2003a, ApJ, 583, 732
Swaters R. A., Verheijen M. A. W., Bershady M. A., Andersen D. R., 2003b, ApJ, 587, L19
Taffoni G., Mayer L., Colpi M., Governato F., 2003, MNRAS, 341, 434
Tassis K., Abel T., Bryan G. L., Norman M. L., 2003, ApJ, 587, 13
Thacker R. J., Couchman H. M. P., 2001, ApJ, 555, L17
Thoul A. A., Weinberg D. H., 1996. ApJ, 466, 608
Tully R. B., Fisher J. R., 1977, A&A, 54, 661
Vale A., Ostriker J. P., 2004, MNRAS, 353, 189
Van den Bosch F. C., Swaters R. A., 2001, MNRAS, 325, 101
Verheijen M. A. W., 1997, PhD thesis, Univ. Groeningen
White S. D. M., Rees M. J., 1978, MNRAS, 183, 341
White S. D. M., Frenk C. C., 1991, ApJ, 379, 52
Wilkinson M. I., Evans N. W., 1999, MNRAS, 310, 645
Zwaan M. A. et al., 2003, AJ, 125, 2842

This paper has been typeset from a TEX/LATEX file prepared by the author.